BRIDGE REHABILITATION PROGRAM WITH ROUTE CHOICE CONSIDERATION

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ABSTRACT

In Thailand, thousands of bridges have been constructed through the national highway network project. With an increasing traffic volume and weights of vehicles, several bridges have deteriorated considerably in recent years. Most of the bridge management systems are developed from an optimization process to search for a solution that provide the maximum utility from selected bridge maintenance projects without considering traffic demand and drivers' route choice behavior on road networks. These methods evaluate utility of the selected bridge rehabilitation plans by assuming additive property of the utility or a simple summation of utilities from different bridges under consideration, which is not the case for road user costs or road network travel times. This research, therefore, presents a new method based on the so-called bi-level formulation to select an optimal bridge rehabilitation plan that minimizes the total road network travel time in the upper level while maintaining drivers' route choice behavior in the lower level. The proposed model is then applied to a study area, which consists of twenty-three bridges on the northern highway network of Thailand. It is found that the model can provide a better bridge rehabilitation plan with the consistent route choice behaviors than the existing models.

1. INTRODUCTION

Transportation facilities are one of the major components of transportation, which account for a major share of public expenditure. Efficient, economical, and safe transportation is critical to a society in meeting its goals toward economic progress, social welfare, and emergency preparedness. Bridges constitute a critical element of any road networks. In Thailand, thousands of bridges have been constructed through the national highway network project. With an increasing traffic volume and weights of vehicles, several bridges have deteriorated considerably in recent years. The Thailand Department of Highways (DOH) is responsible for maintaining the national bridge network. However, only portions of the deteriorated bridges are selected for rehabilitation due to budget limitations.

Given continuously increasing traffic demand, highway agencies confront with difficult questions of how to optimally maintain transportation facilities with limited resources and funds. Most transportation agencies adopt a strategic approach, called transportation asset programming. Programming can be described as the process of selecting and scheduling facility and/or rolling stock preservation improvement, and replacement projects for a transportation network over a period of time. A key element of such a process is to the matching of needed projects to available funds, and to accomplish the strategic goals and objectives set by a transportation agency. The framework of programming should assist both technical and policy decision making by presenting options and the trade-offs in terms of benefits and costs (Kumares, et al. 2007). Most of the bridge programming or management systems are developed from an optimization process to search for a solution that can provide the maximum utility from selected bridge maintenance projects. The NCHRP report 590 presents several optimization formulations to obtain optimal maintenance decisions based on the multi-objective approach. Morcous, G., and Lounis, Z. (2005) presents an approach to determining

the optimal set of maintenance alternatives for a network of infrastructure facilities using genetic algorithms. Optimal maintenance alternatives are those solutions that minimize the life-cycle cost of an infrastructure network while fulfilling reliability and functionality requirements over a given planning horizon. Some methods formulate decision models as a knapsack problem with binary variables, either a bridge is rehabilitated or it is not. These types of formulations are appropriate in transportation programming problems where projects are either entirely selected or entirely rejected in a programming period. There is no partial implementation of projects. In case of bridge rehabilitation with limited budgets, a formulation based on integer programming technique is apposite. Nevertheless, with no consideration on traffic demand on road networks, these methods evaluate utility of the selected bridge rehabilitation plans by assuming additive property of the utility or assuming a simple summation of utilities from different bridges under consideration, which is not the case for road user costs. This is due to route choice behaviors of road users. For instance, an improved network travel time obtained from rehabilitating two bridges is not always equal to the sum of the improved network travel times obtained from rehabilitating each bridge. In other words, we cannot directly superimpose the utilities of the two rehabilitating strategies but they should be considered concurrently. In order to capture the nature of road user costs, traffic assignment should be applied to evaluate road user costs. Traffic assignment is a process of assigning traffic onto a roadway network according to road user behaviors, which is also an optimization model. The most widely accepted concept of traffic assignment is according to the Wardrop's Principle, which states that a stable traffic condition is reached when no traveler can improve his travel time by unilaterally changing routes as mentioned in Sheffi (1985). This is the characterization of the user-equilibrium (UE) condition. From this concept, this study embeds the UE condition as a route choice model in the formulation.

Therefore, an appropriate model should be a bi-level formulation, where the first level is to optimize network travel times with a decision to select bridges for rehabilitation and the second level is traffic assignment model with traffic flows on road network as variables. The objectives of this study are:

- To develop a bridge rehabilitation decision model that can account for route choice behaviors,
- To develop a solution method for the proposed model, and,
- To test the proposed model with a national highway network.

In the remainder of this paper, the problem statement is presented followed by the model development based on a bi-level optimization formulation together with a solution method. The proposed solution method is based on a so-called genetic algorithm. The Genetic algorithm is known to efficiently solve bi-level programs as discussed in Yin (2000). The next section provides an application of the proposed model on a national highway network. The paper is closing with conclusions and recommendations for future research.

2. PROBLEM STATEMENT

In Thailand, the Department of Highways (DOH) is responsible for planning, designing, constructing, and maintaining national highways as well as bridges throughout Thailand. There are now more than 16,000 bridges under the DOH responsibility throughout the country. Recently, the DOH has conducted a bridge inventory survey in the northern part of Thailand as shown in Figure 1.

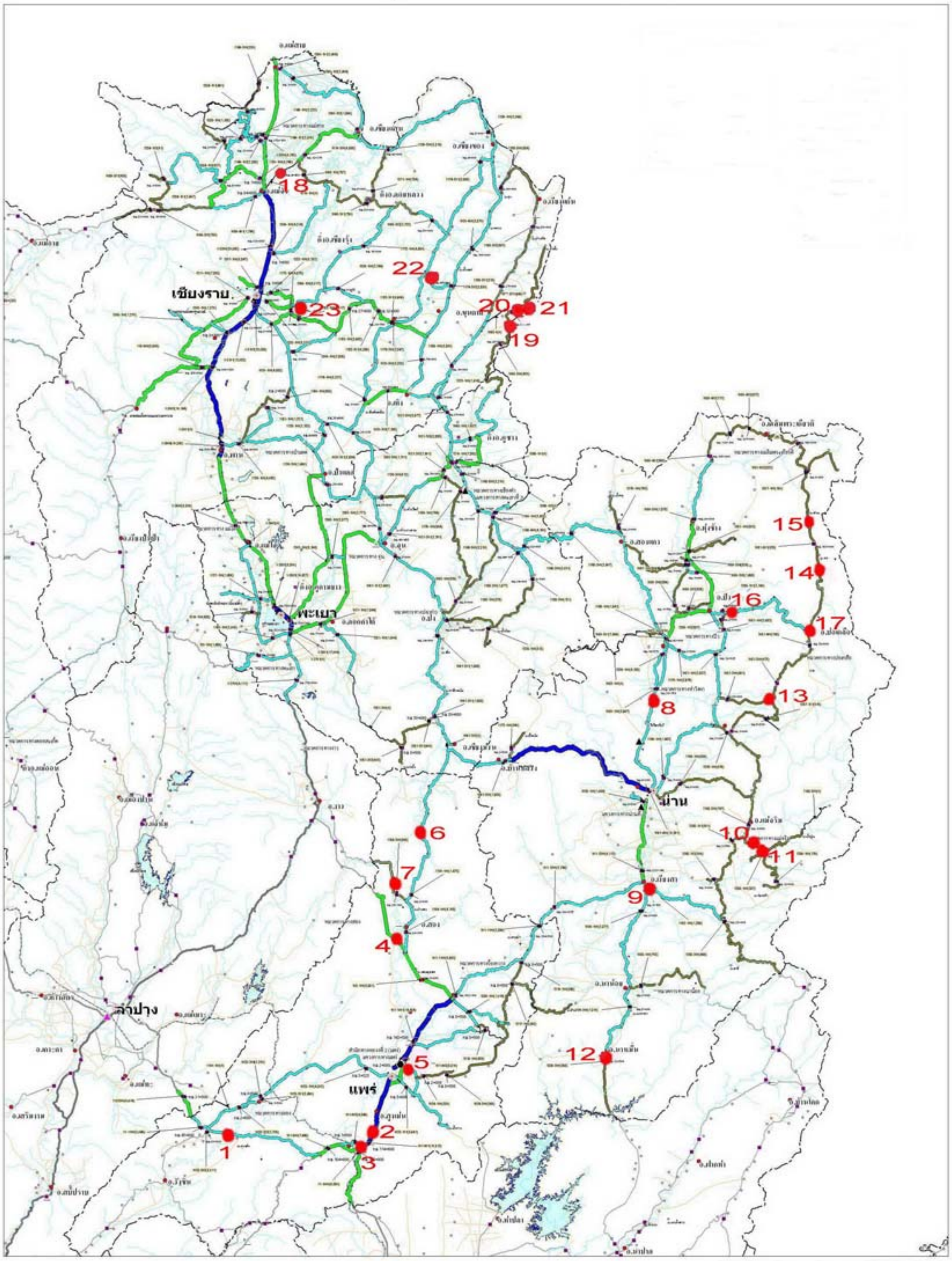

Figure 1: Area under a Bridge Inventory Survey

The area of interest includes 946 bridges, twenty-three of which are severely damaged. These bridges are closed for public use due to safety reason; however, detours are provided. The detours have half of the bridge traffic-carrying capacities. This actually incurs some inconvenience and route diversion to road users. The goal of this study is to determine an optimal bridge rehabilitation strategy with limited budgets so that the total network travel time is minimized. Note that Origin-Destination traffic demand (OD matrix) is available for this network as a result of a traffic survey.

3. MODEL DEVELOPMENT

In this section, a methodology to select the most cost-effective bridge rehabilitation alternatives is proposed. The methodology is developed using the notion of the bi-level optimization

where the first level objective is to minimize total network travel time with a budget constraint and the second level objective is to ensure route choice behaviors under the UE traffic assignment, which was comprehensively discussed in Sheffi (1995). The first part of this section presents the proposed model formulation and the solution method using genetic algorithm is provided in the second part.

3.1 Model Formulation

Consider a highway network where a pair of nodes joined by a link k is associated with a link travel time function, which is a function of its flow and traffic-carrying capacity. As a result of congestion, travel time is a positive and strictly increasing function of its flow. In this study, the link capacity is a function of a bridge rehabilitation decision on the link. As mentioned in section 2, if a bridge is selected for rehabilitation, the associated link capacity on which this bridge is located is as twice as that of the existing condition. Therefore, we can formulate a bridge rehabilitation decision model incorporating route choice as follows.

Upper Level Problem

$$\text{Min Z} = \sum_{k \in \forall\ links} t_k(y_k(x_1,x_2,...,x_N)) \cdot y_k(x_1,x_2,...,x_N) \quad (1)$$

$s.t.$

$$c_1x_1 + c_2x_2 + ... + c_3x_3 \le BUDGET \quad (2)$$

where $t_k(y_k(x_1,x_2,...,x_N))$ and $y_k(x_1,x_2,....,x_N)$ are obtained by solving:

Lower Level Problem

$$\text{Min Z} = \sum_{k \in \forall links} \int_0^{y_k} t(\omega; x_1, x_2,..., x_N)d\omega \quad (3)$$

$s.t.$

$$\sum_{r \in \forall paths} f_r^j = q_j \quad \text{; For all Origin - Destination (OD) pairs "r"} \quad (4)$$

$$y_k = \sum_{j \in \forall ODpairs} \sum_{r \in \forall paths} f_r^j \cdot \delta_{k,r}^j \quad \text{; For all links "k"} \quad (5)$$

$$f_r^j \ge 0 \quad \text{; For all paths "r" and for all OD pairs "j"} \quad (6)$$

Where

$t_k(\cdot) =$ the travel time function of link "k"

$y_k(\cdot) =$ the traffic flow on link "k"

$$x_i = \begin{cases} 1 \text{ if bridge "i" is selected for rehabilitation} \\ 0 \text{ otherwise} \end{cases}$$

$c_i =$ the rehabilitation cost for bridge "i"

$f_r^j =$ the flow on path "r" with OD pair "j"

$\theta =$ the dispersion factor for the LOGIT model

$q_j =$ the traffic demand for OD pair "j"

$$\delta_{k,r}^j = \begin{cases} 1 \text{ if link "k" is on path "r" for OD pair "j"} \\ 0 \text{ otherwise} \end{cases}$$

This formulation indicates that the bridge-rehabilitation-decision model is a bi-level mathematical program. The objective function of the upper-level problem, displayed in Equation (1), is to minimize

the total network travel time with the budget constraint, shown in Equation (2). Travel times and traffic flows on each link are functions of the decision variables on the selection of bridges for rehabilitation. The lower-level problem represents the user's route choice behavior in response to the decision variables on the selection of bridges for rehabilitation. It is assumed that the travelers make their route choices in an user-equilibrium (UE) manner, which is formulated as an equivalent mathematical program. Equations (3), (4), (5), and (6) represent the OD demand conservations, the incidence relationship between links flows in terms of path flows, and non-negativity conditions of paths flows and OD flows. In this study, the Bureau of Public Roads (BPR) cost function is used to evaluate link travel times. However, in order to account for bridge rehabilitation, the BPR function is modified and written as:

$$t_k(y_k; x_1, x_2, \ldots, x_N) = t_k^0 \cdot \left[1 + \alpha \left(\frac{y_k}{CAP_k(x_1, x_2, \ldots, x_N)} \right)^{\beta} \right] \qquad (7)$$

Where

$t_k(\cdot) =$ the travel time on link "k" given its traffic y_k and decision variables $x_1, x_2, \ldots, x_N$

$t_k^0 =$ the free-flow travel time on link "k"

$\mathrm{CAP}_k(\cdot) =$ the traffic-carrying capacity of link "k", a function of decision variables $x_1, x_2, \ldots, x_N$

$\alpha, \beta =$ the BPR parameters with typical values $\alpha = 0.15$ and $\beta = 4$

The traffic-carrying capacity term in Equation (7) is a function of the decision variables. Let us consider a simple network in Figure 2 for an example.

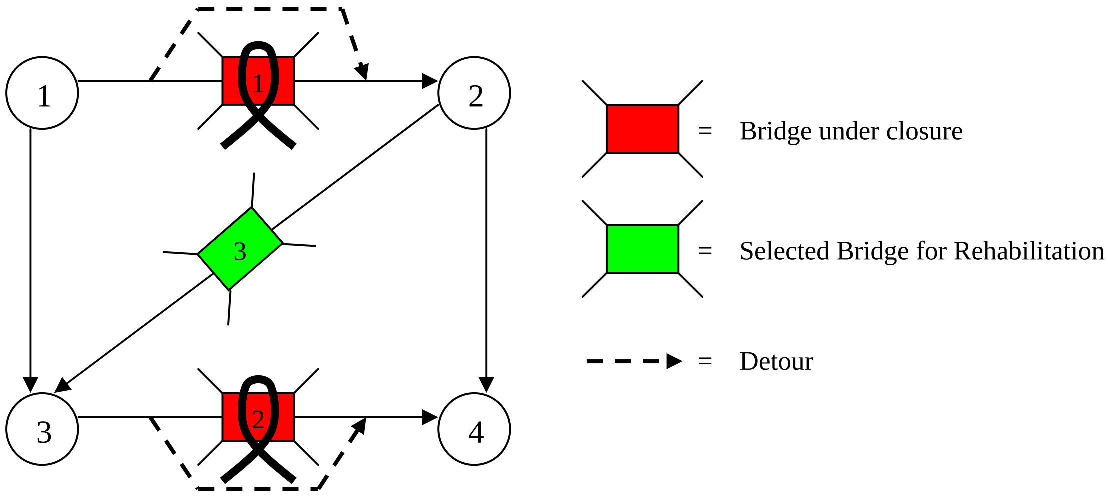

Figure 2: A Sample Highway Network

From Figure 2, bridges number 1 and 2 are under closure but number 3 is not ($x_1 = 0$, $x_2 = 0$, *and* $x_3 = 1$); hence, traffic must use detours to traverse the links 1 to 2 and 3 to 4. These detours have half traffic-carrying capacities when compared to the bridges under closure. A real example of the existing detours is shown in Figure 3.

Figure 3: An Example of the Existing Detour

In fact, the proposed bi-level model is an intrinsic non-convex mathematical program. It is difficult to solve for a global optimal solution. In this study, we use genetic algorithm to obtain a heuristic solution.

3.2 Solution Procedure

The genetic algorithm (GA) is a method for solving both constrained and unconstrained optimization problems and is based on natural selection. The GA repeatedly modifies a population of individual solutions. At each step, the GA selects individuals at random from the current population to be parents and uses them to produce the children for the next generation. Over successive generations, the population evolves toward an optimal solution. The GA uses three main types of rules at each step to create the next generation from the current population:

- Selection rules select the individuals, called parents, which contribute to the population at the next generation.
- Crossover rules combine two parents to form children for the next generation.
- Mutation rules apply random changes to individual parents to form children.

To encode a bridge selection plan for rehabilitation, an individual solution is represented by a string of binary variables as shown in Figure 4. If a binary variable from a specific digit equals one, the corresponding bridge is selected for rehabilitation. Otherwise, traffic traverses the link where the bridge is located must use a detour with half traffic-carrying capacity instead.

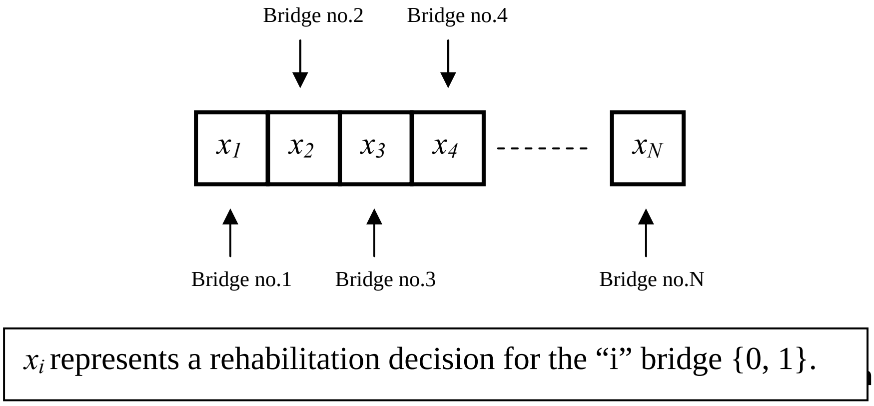

Figure 4: GA – Representation of Bridge Rehabilitation Plan

Given a string of binary decision variables, an individual is evaluated to obtain the fitness value. An individual that violates the budget constraint in Equation (2) will be given with a small value of fitness value. If it does not violate the budget constraint, the lower problem will be solved by a method of successive average (MSA) to obtain the network travel time, which will be converted to the corresponding fitness value for the GA operations in each generation.

4. CASE STUDY

In this section, the proposed model is applied to the study area discussed in the problem statement. The study area consists of a network of the northern national highways and bridges as shown in Figure 1. We abstract the network with links and nodes as illustrated in Figure 5.

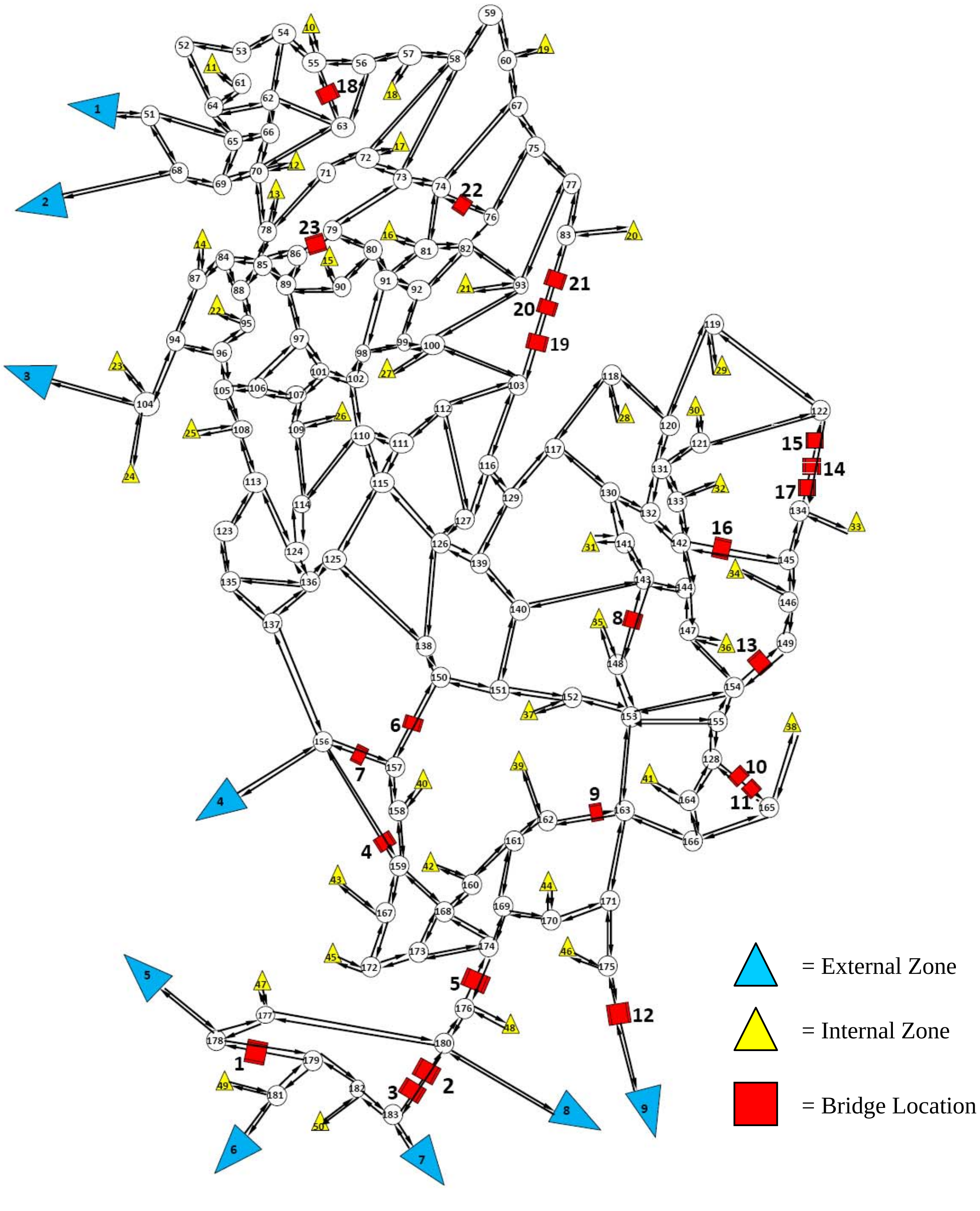

Figure 5: A Node-Link Representation of the Study Network

Note that the bridge survey categorizes bridges into five categories, where category (1) is the most severe damaged and category (5) is new fully functional bridges. According to the survey data, there are twenty-three severely damaged bridges with same damage category (1). Figure 6 shows an example of the bridge in category (1).

Figure 6: An example of the bridge in Category (1)

These bridges are closed for public use due to safety reason; however, detours are provided. The detours have half of the bridge traffic-carrying capacities. This actually incurs some inconvenience and route diversion to road users. Responsible engineers have estimated rehabilitation costs for each bridge as shown in Table 1 with the total required cost of 21,700,000 bahts. In fact, all of them should be rehabilitated; however, due to a limited budget only some can be rehabilitated. Supposed; however, that the available budget is only 7,000,000 bahts. It cannot cover up all required rehabilitation costs. The goal here is to determine an optimal bridge rehabilitation strategy with the limited budget so that the total network travel time is minimized.

Table 1: Bridge Rehabilitation Costs in the Study Area

Bridge No.	Bridge Size (m^2)	Rehabilitation Cost (Bahts*)
1	[ST(4x10)+TG(1x15)+ST(1x10)]x10	500,000
2	[ST(1x8)+ST(1x10)+ST(1x8)]x8	450,000
3	[ST(1x8)+ST(3x10)+ST(1x8)]x8	500,000
4	[ST(1x6)+ST(1x8)+ST(1x6)]x10	500,000
5	[ST(1x7)+ST(3x8)+ST(1x7)]x8	800,000
6	[ST(1x7)+ST(1x8)+ST(1x10)+ST(1x8)+ST(1x7)]x7	500,000
7	[TG(1x25)+TG(2x30)+TG(1x25)]x8	450,000
8	[ST(1x8)+ST(1x10)+ST(1x8)]x7	500,000
9	[ST(1x10)+IG(10x30)+ST(3x10)]x7	1,000,000
10	[ST(1x8)+ST(4x10)+ST(1x8)]x7	800,000
11	[ST(3x10)+BG(4x20)+ST(2x10)]x7	1,200,000
12	[ST(3x7)]x7	800,000
13	[ST(3x10)]x6	500,000
14	[ST(1x5)+ST(3x10)]x6	500,000
15	[ST(3x8)]x6	1,500,000
16	[ST(5x10)]x7	1,000,000
17	[ST(1x8)+ST(4x10)+ST(1x8)]x7	1,250,000
18	[ST(5x8)]x7	350,000
19	[PG(3x9)]x8	200,000
20	[ST(1x5)+ST(1x7)+ST(1x9)+ST(1x7)+ST(1x5)]x8	3,000,000
21	[ST(3x10)+ST(1x8)]x8	4,000,000
22	[ST(2x10)+BG(3x20)+ST(2x10)]x7	1,200,000
23	[PG(3x7)]x7	200,000
TOTAL		21,700,000

Note: * one U.S. dollar approximates 35 bahts.

Travel demand information was obtained through a roadside survey and it is converted to a daily origin-destination (OD) travel matrix. Upon the selection of rehabilitation plan and the loading of travel demand onto this highway network, the total network travel time can be evaluated to obtain an optimal rehabilitation plan.

Upon the application of the proposed model, it is found that an optimal solution is x_1 = 1, x_2 = 1, x_3 = 1, x_4 = 1, x_5 = 1, x_6 = 1, x_7 = 1, x_8 = 0, x_9 = 1, x_{10} = 0, x_{11} = 0, x_{12} = 0, x_{13} = 1, x_{14} = 0, x_{15} = 0, x_{16} = 1, x_{17} = 0, x_{18} = 1, x_{19} = 0, x_{20} = 0, x_{21} = 0, x_{22} = 0, and x_{23} = 1 with the network travel time of 3,757,649,500 pcu-hours. This means that with the available budget bridges number 1, 2, 3, 4, 5, 6, 7, 9, 13, 16, 18, and 23 are selected for rehabilitation, which produce the least network travel time locally. To investigate an optimality of the solution, a sensitivity analysis is conducted by alternating zero-one of each bit from the optimal string. Figure 7 shows the result of this sensitivity study.

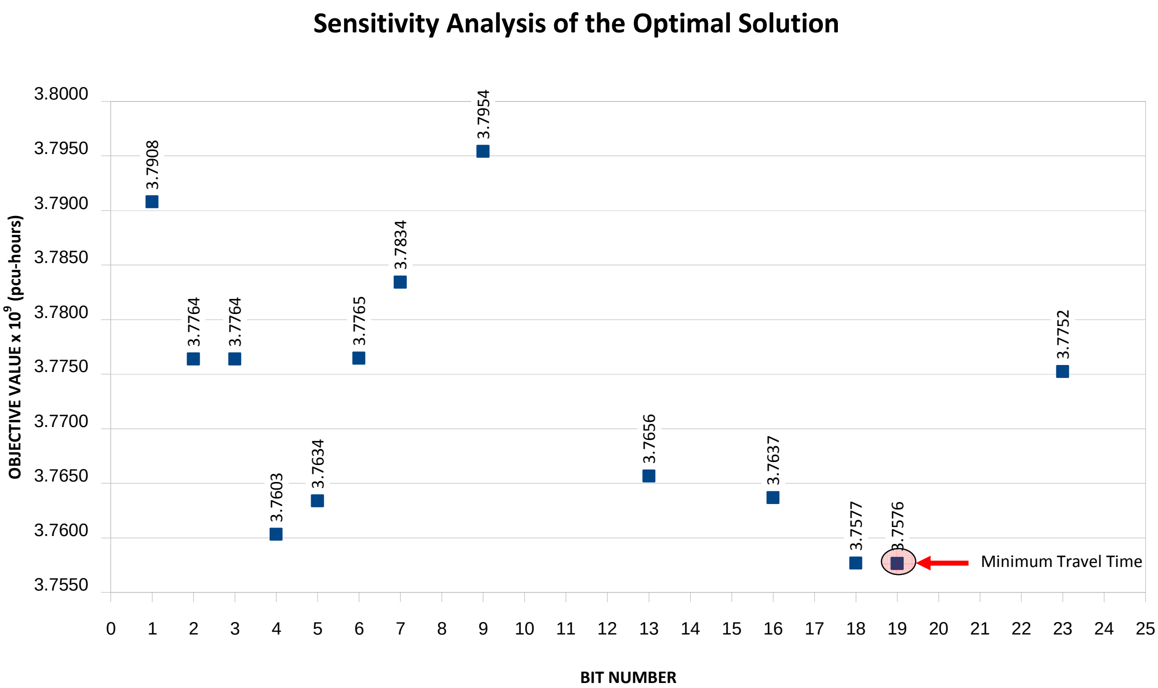

Figure 7: Sensitivity Analysis of the Solution

Obviously, the obtained solution from the proposed model is a good optimal solution because we cannot improve or lower an objective value by changing a rehabilitation decision on any bridge. It is worth noting that flipping bit number 19 from zero to one does not change the objective value. This is due to the fact that bridges number 19, 20 and 21 are on the same road as shown in Figure 5; therefore, selecting only one of these bridges for rehabilitation, while the others are not selected, does not help reduce the objective value. We also examine the validity of a simple summation of utilities, usually assumed in most existing transport programming models, from different bridges under consideration. The utility of each bridge is assumed to equal the travel time reduction corresponding to its rehabilitation without considering others. The optimal solution under this knapsack strategy is x_1 = 1, x_2 = 0, x_3 = 0, x_4 = 1, x_5 = 1, x_6 = 1, x_7 = 0, x_8 = 1, x_9 = 1, x_{10} = 0, x_{11} = 0, x_{12} = 0, x_{13} = 1, x_{14} = 0, x_{15} = 0, x_{16} = 1, x_{17} = 0, x_{18} = 0, x_{19} = 0, x_{20} = 0, x_{21} = 0, x_{22} = 1 and x_{23} = 1. The corresponding network travel time is 3,784,531,800 pcu-hours. Obviously, this solution is different from the one obtained from the proposed model and is certainly not a true optimum because the corresponding network travel time is higher than that obtained the proposed method. Hence, we have demonstrated that the simple knapsack formulation cannot guarantee an optimal solution because route choice behavior is not taken into account.

5. CONCLUSIONS AND FUTURE RESEARCH

This research presents a new method to select an optimal bridge rehabilitation plan that minimizes the total road network travel time with a budget constraint while simultaneously maintaining the consistent route choice behaviors. The proposed methodology is applied to a case study of the northern highway network in Thailand consisting of twenty-three damaged bridges and it is found that the methodology can provide the most cost-efficient bridge rehabilitation plan. The sensitivity analysis is conducted to investigate an optimality of the solution. This solution is also compared to the one obtained from a simple knapsack formulation and it is found that the proposed model can provide a better solution than the simple knapsack in term of the total network travel times. In future, we plan to apply the proposed model to other areas of transportation programming such as pavement management systems and slope-protection management systems at which network travel times are a prime criterion. With a slight modification to the proposed model, bridge or pavement rehabilitation scheduling problems can be solved to obtain optimal construction timing plans that minimize adverse effects of work zones on network travel times. In addition, we plan to include level of toll, fuel price, and distance into the cost function as well.

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